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Interdisciplinary approaches for addressing marine contamination issues

THEMATIC SECTION
Interdisciplinary Progress in Environmental Science & Management

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SUMMARY

Diverse chemical and biological processes in the oceans and atmosphere, the planet's most global domains, determine the fate and effects of marine contaminants and outbreaks of marine nuisance species. Understanding these problems requires the identification of environmental variables that influence ecological and human effects, the ability to predict spatial and temporal occurrences, and development of integrative interdisciplinary and mechanistic models for predicting their occurrences and severity. These endeavours require collaborative efforts of physical, chemical, biological and biomedical scientists working in interdisciplinary teams. There are numerous examples of interdisciplinary research conducted in marine systems on marine contaminants, including those contaminants released from the Earth's crust by human activities, those that are almost exclusively man-made in origin, and those that are biological contaminants often exacerbated by human activities. While interdisciplinary teams of researchers have greatly advanced the study of marine systems in some of these areas, there are still many barriers to interdisciplinary approaches in marine science, including disciplinary biases and institutional structures. A number of mechanisms are recommended that could support and enhance the ability of researchers to conduct interdisciplinary research in marine science, including the establishment of core facilities that can be used to support different teams of collaborating scientists, establishment of appropriate organizational structures, and promotion of seminars and symposia that emphasize interdisciplinary approaches.

Keywords: collaboration, contaminants, interdisciplinary, marine pollution

INTRODUCTION

Increasingly, marine contamination in coastal and open ocean environments has tested the resiliency of the impacted ecosystems and resulted in human health impacts from exposure to contaminated seafood and marine associated diseases. Assessing the consequences of these environmental threats requires physical, chemical, biological, biomedical and social science expertise using interdisciplinary approaches to such complex problems (Hauke *et al*. 2008). The objectives of this paper are to: (1) discuss the need for these interdisciplinary approaches to address some pressing marine environmental issues, (2) describe specific case examples of marine contaminant research that have benefited from interdisciplinary approaches, (3) identify the barriers to the development of interdisciplinary research projects, and (4) recommend mechanisms for fostering interdisciplinary environmental research.

Interdisciplinarity is defined here as integration of knowledge from multiple disciplines combined in a novel synthesis to help explain the dynamics of a complex system, and is often at the intersection of different disciplines (Schneider *et al*. 1995). It typically represents the crossing of traditional academic boundaries or schools of thought and thus involves the collaborative efforts of individuals representing at least two distinct disciplines. The goal is typically to bring together individuals with different skill sets and perspectives to create a holistic understanding of what is usually a complex problem in a way that is more effective than is possible with a non-interdisciplinary approach (see for example Bella & Williamson 1997; Schneider *et al*. 1995).

Numerous marine contamination problems have been identified and studied over the past fifty years. These include: (1) problems that have been exacerbated by human activity, such as oil spills or the presence of potentially toxic metal and metalloid contaminants (for example lead, mercury and selenium) whose mobilization out of the earth's crust is greatly enhanced by man, often at local or regional scales; (2) those stemming from the introduction of contaminants that are almost exclusively man-made in origin, such as synthetic organic compounds, including pharmaceutically active compounds discharged through sewage treatment plants, and radionuclides emanating from the nuclear fuel cycle and weapons fallout; and (3) biological contaminants such as pathogenic microorganisms that can be discharged into coastal waters through human waste water, and harmful algal blooms stimulated by excessive eutrophication. All of these problems are a consequence of human activities and can pose significant risks for marine organisms and human consumers of seafood.

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Moreover, the fates of these contaminants in the marine environment are determined by multiple complex and dynamic environmental factors. Understanding the fate and effects of introduced contaminants in natural waters can be difficult to quantify because the natural environment itself is very complex, and many of the varying environmental conditions can influence contaminant effects. These environmental factors can be thought of as co-stressors and include physical and chemical variables, many of which can change seasonally. There is variability in how diverse marine organisms respond to these variables and to the contaminants themselves. Moreover, contaminants rarely occur alone, and in addition to simple additive effects, significant synergistic and antagonistic interactions can occur among multiple contaminant stressors (Newman 1998; Folt *et al*. 1999; Chen *et al*. 2004). Analysing such interactions among contaminants and diverse environmental factors frequently requires the combined expertise of toxicologists, physiologists, chemists and biostastisticians. Other variables that may be important include how humans interact with and exploit resources in particular bodies of water, with their attendant economic and societal values. Given the diversity of contaminant problems, progress in evaluating the consequences of these problems requires, as much as any endeavour, an interdisciplinary approach that combines the expertise of a wide variety of scientists, including social scientists.

Most studies that have addressed marine contamination problems have considered single issues that were perceived to be of great importance. For example, studies might assess the toxic effects of a given contaminant on an individual species or community, or they might consider the change in a contaminant's concentration in a particular body of water over time. There have been many hundreds of such studies, and while the results have often proven useful for better understanding one aspect of a large and complex problem, they do not address the impacts on a system-wide basis in which interspecific interactions, trophic dynamics, physical and chemical influences, and human interactions with marine ecosystems are all considered.

THE NEED FOR AN INTERDISCIPLINARY APPROACH

In the past, studies on contaminants in natural bodies of water, particularly large ones like the oceans, which were conducted by individuals with only one area of expertise, inevitably had limited success in terms of understanding and predicting contaminant behaviour and toxicity. In recent years, it has been recognized that many areas of expertise are required to make significant headway in moving the field forward. It is clear that an interdisciplinary approach is required, often by combining diverse fields of expertise in the biological sciences (such as ecology, physiology, microbiology, taxonomy and genetics) and the earth sciences (for example oceanography, geology, biogeochemistry and climatology). Often, additional disciplines are also required, such as toxicology, photochemistry, modelling, statistics, epidemiology and risk assessment analysis. Further, to acquire a broader perspective that explicitly includes analysis of environmental contaminant impacts on human populations, the inclusion of social scientists such as economists, human demographers and city planners has become more common. The economic costs associated with individual events measures the impacts of an event in a way that decision makers, many of whom have a limited scientific background, can appreciate. In the field of ecological economics, current research is being conducted in the area of service valuation of ecosystems to assess the loss of ecological value of ecosystems due to human impacts (Farber *et al*. 2006). Some of these studies have addressed coastal and ocean systems and require the interdisciplinary collaborations of marine scientists and economists (Costanza 1999; Farber *et al*. 2006). A case in point would be the massive release of oil by British Petroleum in the Gulf of Mexico in 2010, where detrimental effects on the marine biota were accompanied by large scale financial costs to Gulf residents; even psychological impacts on Gulf of Mexico residents were recognized and may be quantifiable in economic terms. In another example, the 2011 earthquake in Japan led to a devastating tsunami and subsequent damage to a nuclear power plant, which in turn led to release of radionuclides into coastal waters, impairing local fisheries and the Japanese export industry. The economic costs have yet to be realized, but they will amount to substantial sums and will clearly impact the overall Japanese economy, as well as devastate the local economy near the Fukushima nuclear power plant.

The field of oceanography exemplifies, as much as any other scientific discipline, an interdisciplinary field. Graduate programmes in the USA and elsewhere typically require students to take courses in biological, chemical, physical and geological oceanography, in addition to other specialized courses. As a consequence, for those oceanographers interested in marine contaminants, there is a broader appreciation of the breadth of environmental factors that may influence the fate and effects of contamination in the marine environment. Despite this recognition of multiple factors influencing a particular contamination issue, oceanographers frequently have an insufficient background in the key disciplines that are needed to make good predictions of events, assess their impacts and determine appropriate remediation measures. For example, most oceanographers receive relatively little training in toxicology, risk assessment modelling and biochemistry, and usually no formal training in resource economics, public health and other issues that are critical for evaluating the socioeconomic effects of contaminants in marine ecosystems. In this they are not unique among environmental scientists. Therefore, although oceanographers receive a comparatively rich interdisciplinary education with respect to the environmental processes, they still must rely on collaborations with other specialists.

There have been a number of multidisciplinary approaches adopted by scientists to help address some of these complexities, particularly relating to large ecosystem disruptions. The simplest approach has been for individuals with diverse skills and expertise to collaborate on large multi-year projects that cover many of the specific areas relevant to a particular contamination problem and a particular region. Thus, there may be ecologists, toxicologists, geochemists and contaminant analysts involved, and this may be expanded to include public health personnel, risk assessment modellers and economists. A second approach, not necessarily mutually exclusive of the first approach, is to train individuals in more than one discipline so that as individuals they can address a number of critical variables that may influence their findings, and especially recognize the skills that can be applied from other disciplines. Nevertheless, it is clear that regardless of the breadth of training that any one individual may have, no individual scientist could possibly provide all the expertise needed to cover all the key aspects involved in assessing marine contamination events.

Thus, there will always be the need to combine individuals from different disciplines in order for real progress to be made, even though it is recognized here that scientists should receive a sufficient appreciation of the types of skills that individuals in other scientific disciplines can offer. Overall, with interdisciplinary approaches, there is a greater emphasis on a holistic synthetic perspective, often at the expense of clarity of the component details. Unidisciplinary approaches, by contrast, emphasize greater detail, but assemblages, patterns and relationships formed from these details are less apparent (Bella & Williamson 1997).

DIVERSITY OF CONTAMINATION PROBLEMS IN THE MARINE ENVIRONMENT AND COMPLEXITIES IN UNDERSTANDING THEM

While many of the points raised below are commonly recognized or appear self-evident, it is worth underscoring these issues to help justify the need for assembling interdisciplinary teams to address these issues.

The spatial aspects of contaminant distributions are determined by the factors that control their fate and transport. The relevant spatial scales of marine contaminant issues vary greatly from local to regional and often to global. As would be generally expected, many contamination problems are most severe close to large human population centres, particularly those in which there are also extensive industrial or mining activities. Given that a large and growing fraction of the world's population lives within 100 km of a coastline, the pressures that are exerted on coastal ecosystems have increased over time, and this is expected to continue for the foreseeable future. Complicating the chemical and biological contamination issues are habitat destruction due to human development of coastal areas, and this can lead to dwindling nurseries or protective areas for a wide variety of marine animal species. Nevertheless, many contaminants are detected in regions that are far removed from their sites of introduction into the marine environment (for example the pesticide DDT [dichlorodiphenyltrichloroethane] being readily detected in polar regions: Muir *et al*. 1988; Norstrom *et al*. 1988), indicating that ocean currents and wind, especially for atmospherically delivered contaminants, can disperse contaminants globally.

Generally, assessing the environmental fate and transport of these introduced substances can be remarkably complex. Understanding the geochemical cycling of metals, for example, requires identifying and quantifying the mobilization of metals by natural processes (such as through weathering) and by human processes (such as mining or industrial activity), the transport of metals through aquatic and atmospheric media, and the interactions of metals with geological and biological substances; the last can influence the partitioning of metals between solid, gaseous and liquid phases, and the fluxes of metals within different media. Such processes are not only complex, but vary significantly both spatially and temporally with changes in season and changes in human activity.

Studying the effects of organic contaminants is further complicated by the fact that they are often subject to volatilization and photochemical and biological transformations (Schwarzenbach *et al*. 2003). Once organic compounds undergo metabolic breakdown to daughter products, it is necessary to consider the fate and effects of both daughter and parent compounds. This often requires advanced analytical techniques for quantifying and characterizing these compounds. Moreover, understanding the effects of the myriad of compounds on aquatic organisms and humans requires the skills of aquatic (or mammalian) ecologists and toxicologists.

The ability of humans to control outcomes and impacts of marine contaminants depends on the degree to which the impacts can be predicted in time and space and the development of appropriate methods of remediation. Increasingly, there is interest in predicting the occurrence and effects of marine contamination problems, particularly when there are public health issues involved. Predictability of events and their impacts requires, of course, a sufficient understanding of the processes that lead to such events and the mechanisms that lead to detrimental effects. When problems are tied to localized occurrences, such as those tied to point sources of coastal contamination, there are also remediation possibilities, wherein engineering approaches can be used to remove, bury, or sequester released contaminants from a marsh or contaminated sediments in a confined area. Commonly, dredging or capping activities are pursued, but such actions are often very expensive and can lead to a variety of other problems, so responsible parties need to know the likelihood of success or whether their actions might even exacerbate a problem. Thus, applicability of engineered solutions requires sufficient knowledge of the ecosystem being remediated, and often these are very complex, even at the local level. They usually also require modelling studies to evaluate likely future scenarios forecasting mobility, transport and effects of contaminants with or without singular environmental or human changes that may arise. These models, by necessity, take into consideration a large suite of environmental and biological properties in order to provide reasonably accurate estimates of responses to future events.

It becomes immediately apparent that understanding such issues requires a thorough understanding of the biogeochemical cycling of the contaminants and the influence of food chain dynamics on their bioavailability, including the food web dynamics in a particular ecosystem (Fisher & Reinfelder 1995; Wang & Fisher 1999; Luoma & Rainbow 2008; Mathews & Fisher 2009). For evaluating public health consequences, human demographics, dietary habits, human toxicology and biochemistry are clearly required. Thus, the answer to a simple question like 'Is it safe to eat the seafood here?' requires the combined integrated responses of toxicologists, geochemists, marine ecologists and social scientists.

These issues of contaminant source, fate, bioavailability, and the ecological and human risks that result are inherent in a wide range of marine contaminant problems. Here we briefly describe examples of several types of marine contaminants, including toxic chemicals and biological threats. These contaminants vary greatly in their sources and the spatial and temporal dimensions of the threats that they pose. Each has given rise to many studies, including interdisciplinary studies involving collaborators from around the world.

Mercury

Mercury is a ubiquitous metal in the environment that comes from both natural and anthropogenic sources. Currently, the largest human source is coal combustion in power plants, although gold mining activities and diverse industrial sites such as chlor-alkali plants can serve as important point sources of mercury in different regions. Mercury is atmospherically transported from these sources and eventually deposited in aquatic ecosystems, where the conversion of some of the inorganic mercury to methylmercury can occur (Driscoll *et al.* 2007; Fitzgerald *et al.* 2007). Methylmercury is the toxic form of mercury that causes neurological impairment in humans and wildlife (National Academy of Sciences Committee on the Toxicological Effects of Methylmercury, Board on Environmental Studies and Toxicology, National Research Council 2000; Mahaffey *et al.* 2004; Mergler *et al.* 2007). It is also retained effectively in tissues of biological organisms and is biomagnified in marine food webs (Campbell *et al.* 2005; Chen *et al.* 2008). In marine systems, mercury concentrations in top predatory fish species such as tuna, swordfish, shark and marine mammals are at levels that may result in exposure risks to humans consuming large quantities of them (Clarkson 1998). Arguably, the greatest single instance in which a contaminant of any kind in a marine ecosystem interfered with human health occurred in Minamata Bay, Japan, where many human deaths and severely impaired individuals resulted from the consumption of seafood harvested from a heavily contaminated bay. There is currently disagreement about what mercury concentrations in seafood are acceptable, or even what concentrations in human blood can elicit toxic responses. This is an area of active research with many far-reaching implications, further complicated by the fact that essential fatty acids are especially enriched in many forms of seafood. Thus, for cardiovascular reasons and for healthy brain development in fetuses, physicians often recommend a seafood-rich diet. But a diet rich in those seafood items that are also rich in methylmercury can also pose risks.

The environmental fate of mercury has been investigated by atmospheric chemists and modellers, biogeochemists, and terrestrial, aquatic and microbial ecologists. Sources are frequently atmospheric, but transformations from inorganic forms to the toxic methylmercury species are due to microbial processes, and transport and uptake processes occur in forest, freshwater and marine ecosystems. Thus, it critical to evaluate processes at scales ranging from the sub-micron to thousands of kilometres.

The toxicity of mercury, like any other chemical, is dependent on conditions and processes that favour uptake and assimilation, and the mode of action of the toxicant. In the case of mercury and other metals, the speciation greatly determines the bioavailability and toxicity, monomethylmercury being the most toxic of the common environmental forms. The proportion of total mercury that is methylmercury increases with each level of the food web, such that values can increase from *c*. 10% in phytoplankton to >90% in fish (Driscoll *et al.* 2007). This enrichment in methylmercury with increasing trophic level (biomagnification) is attributable to the fact that methylmercury displays high assimilation efficiencies in marine animals (often 80–100%) and very slow loss rates, in contrast to inorganic mercury, where assimilation efficiencies are typically <10% and loss rates are comparatively rapid (Mathews & Fisher 2008). Thus, as a fish grows older, it keeps acquiring methylmercury but loses little of it, and thus concentrations in tissue increase with age. Full understanding of methylmercury uptake, effects in aquatic food webs, and exposure of wildlife and humans requires the combined expertise of trace metal chemists, biogeochemists and toxicologists.

This aspect could perhaps be the most important when it comes to influencing environmental policy. Ecological and human risk is largely determined by the route of exposure, which in this case, is fish consumption for both humans and wildlife. Included in questions of risk are the issues of exposure and effects. Questions of exposure are related to occupational exposures or consumption of fish. Methylmercury is able to cross the blood brain barrier, as well as the placenta, making it particularly toxic to the developing fetus and young children (Clarkson 1998, 2002). The human endpoints for determining effects of Hg range from developmental and learning endpoints in newborns and children to neurological and cardiovascular endpoints in adults. Impacts of intermediate concentrations of methylmercury to adults clearly require further study. Exposure and effects in piscivorous wildlife have also been documented and range from behavioural alterations in birds and fish to hormonal and reproductive impairment (Evers *et al*. 2005).

Chlorinated hydrocarbons

This group of contaminants includes the extensively studied pesticide DDT, and a group of industrial compounds, most particularly polychlorinated biphenyls (PCBs). The use of many chlorinated hydrocarbon compounds (such as DDT and PCBs) in the USA and elsewhere has been banned. Nevertheless, due to the massive quantities that have been used in the past, and their mobility and persistence in the environment, their residues remain ubiquitous in diverse marine biota (including those inhabiting regions far from the original sites of use), as well as in water and sediment.

These compounds are distinguished by having great persistence in the environment under 'normal' environmental conditions, including comparative resistance to biological degradation (Newman 1998). The latter does occur, but typically at far lower rates than those exhibited by many other organic compounds, including some components in crude oil, for example. As a consequence, chlorinated hydrocarbons often fall into the broader category of persistent organic pollutants (POPs). Further, they have very low solubility in water and high solubility in lipids, hence they display high partition coefficients for suspended particles, including living organisms (Schwarzenbach *et al*. 2003). Their solubility properties result in their deposition in lipids in individual cells (for example, in lipid bilayers in membranes) and in the fatty tissue of animals (Matthews & Dedrick 1984; Schwarzenbach *et al*. 2003). These compounds consequently are greatly enriched in living organisms relative to ambient seawater, comparable to the most particle-reactive metals, and also commonly display biomagnification in aquatic food chains, where diet is the predominant source for aquatic animals (Muir *et al*. 1988; Thomann 1989; Evans *et al*. 1991; Broman *et al*. 1992; Gobas *et al*. 1993; Kidd *et al*. 1995; Fisk *et al*. 1998), not unlike methylmercury. Thus, concentrations of the most hydrophobic compounds can be enriched in tissues by a factor $>10^5$ times that in seawater, and food becomes the most important source of these compounds for animals, including people. High concentrations of chlorinated hydrocarbons can be found in human mother's milk, particularly in some polar areas where seafood is an important component of the diet and where marine animals have high levels of fatty tissues as an adaptation to a cold climate (Hansen 1998; de March *et al*. 1998). The public health consequences still require further study.

Chlorinated hydrocarbon compounds can be toxic to a broad spectrum of living organisms, ranging from single-celled phytoplankton cells to macroinvertebrates and mammals, including man (Newman 1998). They received considerable attention in the 1960s and 1970s, initially due to their negative effects on the reproduction of marine birds. In addition to environmental effects, they have been considered as possible human carcinogens (Safe 1989; Silberhorn *et al*. 1990). Studies that have focused on the fate and effects of chlorinated hydrocarbons, as well as other toxic organic compounds, have frequently focused on their degradation pathways, often involving microbial metabolic breakdown because these organisms can influence the extent to which these compounds persist in toxic forms in the environment. As with the other contaminants discussed here, it is clear that understanding the distribution, persistence and consequences of chlorinated hydrocarbons in marine ecosystems requires teams of scientists that include organic chemists, atmospheric scientists, benthic and pelagic geochemists, and toxicologists. For toxicology, this can include toxicity studies focusing on simple one-celled organisms, toxic effects on more complex animals where distinct organs or endocrine function can be impacted (Crisp *et al*. 1998; de March *et al*. 1998; Kime 1998), and even carcinogenic effects in fish and mammals. Further, some of the most expensive environmental engineering schemes to remediate impacted ecosystems (often involving dredging), such as with PCBs in the Hudson River, have involved the chlorinated hydrocarbons, and evaluating the risks of such activities on chlorinated hydrocarbon concentrations in aquatic organisms can be complex (von Stackelberg *et al*. 2002). Such remediation efforts clearly require the input of interdisciplinary teams that include sediment geochemists, engineers and aquatic ecologists.

Radionuclides

Another example of contaminants that have entered the oceans exclusively through human activity is the input of long-lived anthropogenic radionuclides. Most of these radionuclides were introduced following nuclear weapons-testing in the early 1960s, although weapons-testing has continued at a greatly reduced rate since then. The radionuclides released through weapons-testing were carried throughout the globe and have been identified as present in the most remote regions of the earth (Park *et al*. 1983; Strand 1998). Accidental discharge of radionuclides (such as occurred during the Chernobyl incident in 1986 and the Fukushima incident in 2011, and as a consequence of losses of nuclear-powered ships) and intentional release of radionuclides from the discharge of radioactive wastes from nuclear reprocessing plants (for example Sellafield in the UK) and other nuclear facilities have resulted in greatly increased concentrations of some radionuclides (such as ^{137}Cs and ^{239}Pu) in some marine waters, usually localized (Linsley *et al*. 2004; Vintro *et al*. 2004). Additionally, there has been serious interest in using the seabed as a disposal option for long-lived radioactive wastes emanating from the nuclear fuel cycle (Hollister *et al*. 1981; Miller *et al*. 2000). Thus, there is concern about the distribution of long-lived radionuclides on global scales as well as localized scales (for example in a particular bay, a regional sea or a particular dump site).

In part owing to the public's fear of radioactivity, a number of long-standing monitoring efforts have been implemented to track the fate of these materials. These studies are motivated principally by risk assessment efforts to protect the public, and require input from modellers that consider bioaccumulation, hydrodynamics, sediment transport, the physical and chemical properties (including radiological half-lives) of specific radionuclides, and the dose-response patterns for distinct types of radionuclides (Hinton 1998; Hunt 2004). Particular attention has been paid to establishing whether sufficiently high concentrations were accumulated in resident organisms (Fowler & Fisher 2004) that could affect the organisms themselves or pose a significant risk for human consumers of seafood from that region (Hunt 2004). Similarly, simulation studies by teams that include physical oceanographers, ocean engineers, biogeochemists and risk assessment modellers have been conducted to evaluate the likely impact of radioactive wastes disposed on or under the seabed in different ocean basins (Marietta & Simmons 1988). In order to unambiguously interpret the monitoring data or generate reasonably realistic simulations of disposed wastes, as well as to predict the consequences of future releases, many studies have been necessary to increase fundamental understanding of the cycling and fluxes of radionuclides in marine systems, their bioaccumulation in diverse marine organisms and their toxic effects on these organisms.

Modelling studies have been conducted to evaluate the likely radioactive dose to man for each radionuclide of interest based on bioaccumulation studies, seafood consumption patterns among different human populations and oceanographic transport studies that describe the movement of the radionuclides in different 'compartments' of the ocean; risk assessment efforts have then been conducted to evaluate the estimated human health impacts attributable to seafood consumption (Hunt 2004). This kind of interdisciplinary approach has served as a model for other contaminant studies involving the oceans. By combining empirical and modelling studies, and by combining biogeochemical processes operating on both global and local scales to such disparate issues as radioisotope half-lives, human diets and fundamental studies of radiotoxicity, quantitative estimates have been generated to predict the impacts on human health (for example the number of cancers arising in a human population over a specified period of time) resulting from releases of discrete radionuclides.

Cholera

Cholera has been an important infectious disease of humans for millennia, and its cause is the pathogen, *Vibrio chlorae*. The earliest records of occurrence date back to Sanskrit writings in 5–500 BC. There have been multiple pandemics of cholera in Asia, Africa, Europe, North and South America, but mostly associated with coastal populations and therefore its origins are strongly associated with marine environments (Colwell 1996). The species *V. cholerae* is comprised of multiple biotypes, some of which cause epidemics of diarrhoea (*V. cholerae* 01, 0139, 01 El Tor), while others do not. These microorganisms optimally grow in seawater of 5–25 parts per thousand salinity (Constantin de Magny *et al*. 2009). They are associated with marine plankton by attachment to the carapace and guts of zooplankton hosts. Thus, their prevalence is inextricably tied to the environmental factors promoting plankton growth.

The environmental sources of cholera are largely marine, although the microbe is transmitted in riverine, estuarine and coastal waters mainly in temperate and tropical regions (Constantin de Magny *et al.* 2008). Environmental predictors of cholera epidemics have included sea surface temperature and height, rainfall, plankton densities and salinity, and their occurrences have been associated with El Nino events (Lobitz *et al*. 2000; Constantin de Magny *et al.* 2008; Akanda *et al.* 2009; Paz 2009; Cash *et al*. 2009). Rainfall events that result in increased nutrient inputs from nearby watersheds also result in phytoplankton blooms and subsequent zooplankton blooms. Since each copepod can carry 10^4 cells of *V. cholerae*, an infectious dose of 10^3 cells is easy to achieve in tidal rivers. The use of remote-sensing data and the development of predictive mathematical models of the occurrence of cholera outbreaks are areas of active research by physical oceanographers and mathematical modellers. Like other marine contaminant problems, investigations occur at a wide range of scales, from the sub-micron level to thousands of kilometres.

The virulence of *V. cholerae* is due to a number of toxins found in the O1 and O139 strains. Although the effects of these toxins on cellular function are well characterized, the molecular mechanisms are not fully understood and these are an area of intense research. Studies have been conducted in a number of animal models, including mice, rabbits and nematodes. Much of this research is conducted by toxicologists and molecular biologists. Humans are exposed to *V. cholerae* largely through drinking contaminated water. Studies have shown that water treatment, including filtering out zooplankton prior to drinking, influences the rate of infection. Socioeconomic status also influences cholera occurrence due to its relationship to poor water quality and sanitation in poorer households (Emch *et al*. 2010). The epidemiological and sociological aspects of cholera infection and transmission are also important research topics. Identification of these socioeconomic factors is critical to determining spatial and temporal predictors of cholera outbreak.

Harmful algal blooms and human health effects

Harmful algal blooms (HABs) can occur as dense blooms of cells or in non-visible low densities, all of which threaten living marine resources and human health. The algal species that comprise HABs are a diverse group of organisms that range from single-celled phytoplankton to macroalgae. They are increasing worldwide primarily due to eutrophication of coastal waters and the transport of toxic cells or their cysts through shipping. Their impacts include human illness and death from ingesting the toxins in contaminated seafood and mortalities of marine organisms, including fish, mammals and seabirds (Anderson 1997; Van Dolah 2000). The causes of these blooms are not well understood, but their causes, effects and detection are the focus of interdisciplinary research across a wide range of fields.

The hypothesized causes of the increasing frequency of HABs include nutrient enrichment due to human land use in coastal watersheds and transport via currents and storms or ballast water (National Science and Technology Council 2000). The nutrient hypothesis has been investigated, but has been difficult to confirm given the diversity of nutrient requirements of different species and the lack of historical data on nutrient inputs to coastal ecosystems. The environmental factors causing the proliferation of HAB species have been investigated in coastal environments all over the world by biological and physical oceanographers (Brand & Compton 2007).

The toxic effects of HABs result either from chemicals that are released by certain species of algae, the harm caused by dense aggregations of non-toxic cells on fish gills, or anoxia resulting from degradation of the blooms. These impacts have severe commercial and recreational consequences for fisheries, tourism and recreation (Hoagland *et al*. 2009; Dyson & Huppert 2010). The severity of the human and environmental health effects of red tides has resulted in research on exposure and effects on humans, including respiratory effects of aerosols (Fleming *et al*. 2009; Hoagland *et al*. 2009). The range of disciplines that are required to address this environmental problem includes phytoplankton ecologists, wildlife biologists, ecotoxicologists, toxicologists, economists and a diversity of social scientists.

The economic and environmental health consequences of HABs have stimulated a great deal of research on methods of detection and for the prediction of HABs. The methods include using satellite remote sensing to detect red tides, molecular tools for distinguishing non-toxic species from toxic species, cell sorting methods using flow cytometry, and bead arrays and electrochemical biosensors for detection (LaGier *et al*. 2007: Dyhrman 2008; Scorzetti *et al*. 2009; Sinigalliano *et al*. 2009; Carvalho *et al*. 2010; Diaz *et al*. 2010). These techniques are being developed by physical oceanographers, molecular biologists and phytoplankton taxonomists, and require addressing questions at scales ranging from subcellular to entire oceans.

BARRIERS TO MOUNTING SUCCESSFUL INTERDISCIPLINARY RESEARCH

Assembling interdisciplinary teams to address complex issues is difficult for a variety of reasons. At the level of individual researchers in different disciplines, there are barriers in language, paradigms and approaches. It can be difficult to assemble individuals who do not know one another and come from disparate disciplines to converge on a single goal or set of goals. For example, addressing complexities involved in large marine contamination studies requires forging teams of scientists from the natural science community, the engineering community and the social sciences. For each discipline, there are established patterns and procedures for addressing problems that are well accepted within each field; in contrast, interdisciplinary approaches may be far less established and involve greater uncertainty in terms of acceptance in any of the fields.

Different disciplines are also often entrenched in a particular way of addressing a scientific problem and fail to recognize the value of an alternative approach. The language and focus of social scientists can be so distinct from the natural and engineering sciences that it is difficult for all participants of a joint study to comprehend the goals and terminology of documents describing the principal findings of an interdisciplinary study. Harmonic coordination of different disciplines may be compounded by fundamentally different approaches, such as the problem-solving approach pursued by engineers, the clinical approach pursued by the medical community, and the analysis of fundamental processes pursued by geoscientists.

There are also institutional barriers to interdisciplinary research. Large research universities, which often dominate the research efforts in specific fields, tend to house their faculty in separate departments, frequently situated in distinct academic units, each headed by a different dean. These different departments and schools are often situated in different locations on a particular campus, or even on different campuses, and these geographic separations tend to exacerbate the separation of the different disciplines. Further, while there can be lip-service paid to the virtues of interdisciplinary research, faculty promotions and tenure depend largely on demonstrated progress within a particular field, usually quite focused and often narrow. Interdisciplinary research is not necessarily appreciated in academic institutions, where it is sometimes regarded as 'soft science', and an individual who is engaged in such efforts is seen as a 'Jack of all trades and master of none.' A similar kind of departmentalization can also be seen in national laboratories, even those that address environmental issues. Nevertheless, there has recently been a striking increase in interdisciplinary environmental education programmes in universities in the USA, and it is expected that some of these reservations about interdisciplinary approaches in academia will diminish in the coming years to accommodate the many new faculty hired to support these programmes.

The grouping of disciplines into different departments can influence the types of interdisciplinary collaborations that form. For example, marine microbiologists might be trained in marine science programmes or in more classical microbiology departments, and are likely to be professionally situated in either a microbiology department or an oceanography department. Under most circumstances, they are unlikely to professionally interact with, for example, economists, geologists or theoretical ecologists. But if they were housed in an oceanography department they would likely interact regularly with other marine scientists representing a variety of

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disciplines (for example physical oceanographers, geochemists or marine zoologists). If they were located in a microbiology department, they would probably interact with molecular biologists, cell physiologists or geneticists. In either case they would be unlikely to interact with engineers, toxicologists or contaminant analysts and, if they were in an oceanography department, they would probably not regularly interact with biomedical scientists. This sort of separation would be typical for all specific disciplines, not just microbiology.

Yet another barrier to interdisciplinarity is the perception that it is difficult to publish results of interdisciplinary research in a specialized or high-quality journal, and that publications of such projects would be overlooked. This perception has, in fact, not been supported by publication data however, at least in the field of forestry where they found that published studies that drew information from a diverse set of journals were cited with greater frequency than articles having smaller or more narrowly focused citations (Steele & Stier 2000). Nonetheless, scientists in different disciplines publish in different journals and there is often little broad readership for many specialized journals. There are, of course, a few journals that publish studies of interest to the broader scientific public, such as *Nature* and *Science*, but these journals typically publish very short papers that cannot capture the many details and nuances needed to describe a comprehensive study involving complex environmental problems. Thus, through publications, science can sometimes become 'Balkanized', and there is often little common ground appreciated by the broader scientific community.

These barriers to interdisciplinary research also exist at the level of funding agencies. Some agencies have recognized the need for a multidisciplinary approach to tackle large complex issues, such as those involving ecosystem impacts and restoration in a large bay or watershed. These agencies often encourage studies to encompass the social sciences, together with the natural and engineering sciences, or encourage collaborations of medical and non-medical personnel to address complex environmental problems that may impact public health. However, even the funding agencies themselves can become Balkanized, wherein there is reluctance on the part of one section of a large agency to support research that is seen as something that should be supported financially by a different section of that same agency. As a consequence, the responsibility for handling or taking ownership of interdisciplinary projects can elude administrators, particularly those individuals in large agencies that are most comfortable in processing grant proposals that are focused and fall within a single discipline. This problem can occur between different sections of a given agency or between different agencies when more than one agency chooses to co-fund large projects.

Strong leadership at funding agencies is also needed to ensure that interdisciplinary projects are not subject to undergoing twice the scrutiny (and often twice the risk in getting funded) that a normal project would receive in the review process or be vulnerable to funding idiosyncrasies unique to a particular agency that would not occur in a unidisciplinary proposal. Grant proposals submitted to a funding agency are often handled by scientists in a more-or-less confined discipline, but, if the proposal seeks to pursue interdisciplinary research, it is often necessary, and indeed appropriate, to have it reviewed by scientists in each of the specific research fields. Thus, the proposed work must be rated as excellent in more than the customary one discipline, and hence the likelihood of success is often diminished compared to more focused unidisciplinary proposals.

For successful interdisciplinary projects, individuals involved need to adopt an attitude that unidisciplinary approaches have limitations in generating a holistic view of a complex problem and need to agree on overcoming the inevitable confusion that may arise in as collegial a way as is possible. Overcoming gaps in understanding among different disciplinary participants and appreciation of different disciplines requires a conscientious effort by the diverse participants and a willingness to cooperate. It often also requires strong leadership from a team leader to ensure that all participants maintain a spirit of cooperation and acknowledge the worth of scientific approaches distinct from their own.

FACILITATING INTERDISCIPLINARY APPROACHES FOR EVALUATING MARINE CONTAMINATION PROBLEMS

While examples of interdisciplinary research on marine contaminants have been described above, the barriers to these types of collaborations do still exist. Beyond the recognition that multiple disciplines need to interact in order to address complex environmental problems, a number of approaches have been used to actively foster interdisciplinary research. A few examples are discussed below.

Funding for interdisciplinary programmes

Research programmes that are structured to include a wide range of disciplines and that require demonstration of the linkages between those disciplines provide an effective means for encouraging scientists of different backgrounds to develop interdisciplinary research questions. In some cases, these programmes require collaborations between biomedical and non-biomedical scientists or natural scientists and social scientists. In all cases, the targeting of research funds toward these joint endeavours results in interdisciplinary research and encourages communication, language and approaches that bridge different disciplines. Moreover, when these programmes provide funds for training graduate and postgraduate students, a new generation of scientists and social scientists can emerge that will assume that interdisciplinary projects are the only way to conduct cutting-edge research. Examples of such successful ID programmes include the previous National Science Foundation programme entitled 'Biocomplexity in the Environment: Integrated Research and Education in Environmental Systems' (see URL http://www.nsf.gov/pubs/2003/nsf03597/nsf03597.html), which emphasized interdisciplinary approaches focusing on complex environmental systems that exhibit non-linear behaviour; the current 'Dynamics of Coupled Natural and Human Systems' (see URL http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13681&org=NSF&sel_org=NSF&from=fund), which promotes interdisciplinary analyses of relevant human and natural system processes and complex interactions among human and natural systems at diverse scales; and a more marine focused interdisciplinary programme, the USA's National Oceanic and Atmospheric Administration's 'Oceans and Human Health Initiative', which attempts to foster interdisciplinary collaboration of ocean, biomedical and public health researchers, resulting in rapid application of new findings to protect human health and coastal environments. While these programmes all support important interdisciplinary research, they are all underfunded and sometimes diminishing in size rather than growing to meet the complex environmental challenges ahead.

Another example is the Superfund Research Programme (SRP) of the National Institutes of Environmental Health Sciences (NIEHS, see URL http://www.niehs.nih.gov/research/supported/srp/funding/rfa.cfm), which funds multidisciplinary programmes that integrate biomedical research with related engineering, hydrogeological and ecological components to address the broad complex health and environmental issues that arise from the multimedia nature of hazardous waste sites. The SRP funds programmes in 14 academic institutions in the USA, of which the Dartmouth SRP is a good example. In all of the programmes, there must be demonstrated links and collaborations between the biomedical and non-biomedical research projects, as well as analytical cores. Moreover, there are research translation and outreach cores that also integrate the different fields represented by that wide range of projects. At Dartmouth College, the SRP is a toxic metals programme where scientists, including epidemiologists, trace metal chemists, ecologists, molecular biologists and geologists, have worked together for over 15 years to investigate the mechanisms and processes controlling environmental and human exposure, and effects of toxic metals. The mandated training cores also produce a new generation of interdisciplinary researchers who can naturally forge relationships with individuals in other fields.

Core facilities

Research programmes or institutions that have core facilities, such as analytical or public 'outreach' cores, foster interdisciplinary interactions, since the cores provide a service or function that can be used by researchers from a wide variety of disciplines. For example, chemical analytical cores are run by organic or inorganic chemists, but used by toxicologists, ecologists, biogeochemists, epidemiologists, molecular biologists and geneticists. Thus the collaboration between the core scientists and the users is by nature interdisciplinary, and there are also collaborations that can form between users in different fields.

Workshops and seminars

The opportunity for individuals of different disciplines to gather in either workshop or seminar settings to share their perspectives, research problems and ideas creates multidisciplinary networks that foster the interpersonal relationships necessary for interdisciplinary collaboration to occur (Schneider *et al.*, 1995). These can be cross-department seminars or workshops for individuals from multiple institutions. A number of agencies provide funds for organizing and holding interdisciplinary workshops and conferences (for example the NIEHS, see URL http://www.niehs.nih.gov/research/supported/srp/resources/index.cfm). These meetings are excellent venues for initiating conversations and collaborations between experts in different fields. They are particularly useful if the workshop facilitators organize the presentations and discussions around topics at the interfaces of different fields and set goals for producing interdisciplinary products such as synthesis papers or research proposals.

Academic departments or programmes that are interdisciplinary

There are growing numbers of institutions building departments and programmes that are explicitly interdisciplinary and bridge more traditional departments in those institutions. Environmental science or studies departments are becoming common in many universities, and often include natural scientists and social scientists (for example ecologists, geochemists, economists and geographers). Oceanography departments are also by nature, interdisciplinary given their inclusion of biological, chemical, physical and geological oceanographers as well as ocean engineers. Moreover, there are a growing number of 'sustainability programmes' or 'global change programmes' that provide transdisciplinary and interdisciplinary training to solve complex global problems. Arizona State University's School of Sustainability, established in 2004 (ASU, see URL http://sustainability.asu.edu/about/index.php), offers transdisciplinary degree programmes focused on 'finding practical solutions to environmental, economic, and social challenges in urban settings'. The Earth Systems Programme at Stanford University (see URL http://earthsystems.stanford.edu/) is an interdisciplinary programme for undergraduates who become 'skilled in those areas of science, economics, and policy needed to tackle the globe's most pressing environmental problems.' Most of these interdisciplinary programmes are made up of faculty from traditional disciplinary departments who have appointments in these specific programmes.

Another example of an attempt at fostering interdisciplinary environmental research without altering the traditional academic structure can be found at Stony Brook University in New York. The university provided funds to create the Consortium for Interdisciplinary Environmental Research (CIDER; see URL http://www.stonybrook.edu/cider/) and provided resources for hiring new CIDER-affiliated faculty in tenure-track lines, with each individual located in one of the existing academic departments. The administrators and faculty of these departments understood at the time of hiring that these newly added faculty members would have an obligation toward collaborating with CIDER faculty in other departments, as well as fulfilling their own departmental obligations. By creating CIDER, the university helped create a platform that enables it to respond to large interdisciplinary funding opportunities that would otherwise be difficult to attain.

It is the expectation that within these interdisciplinary departments or academic units that an individual's progress and evaluation for promotion would not be dependent solely on their success in only a single narrow field as is often expected in more traditional academic units. Moreover, universities should provide resources to foster interdisciplinary collaborations to enable meaningful research teams to form across departments to address the many complexities involved in environmental contamination studies. One mark of success of an interdisciplinary approach to environmental research, including marine contamination problems, would be successful acquisition of external funding and resources (such as those described above) that would otherwise be unavailable to more narrowly focused research efforts, and once funded that the resulting research findings would be a case where the 'whole is greater than the sum of its parts' due to synergistic interactions between different specialists. This could be measured not simply by the number of papers that are produced, but the scope of the papers that are produced, many of which could appear in the ever growing number of interdisciplinary journals.

CONCLUSIONS

In the marine sciences there are numerous examples of interdisciplinary research teams and collaborations that have brought great benefit to the understanding of the fate and effects of marine contaminants, both chemical and biological. The examples presented here illustrate the range of disciplines required, the spatial scales over which these contaminants are transported from their sources and the biological levels at which they exert their effects. The breadth of the regional seas and oceans in which these contaminants are distributed is measured on the order of thousands of kilometres, whereas the organisms that either cause these problems or are impacted by them can be measured at the level of microns. The tools and models for measuring and predicting the effects of the contaminants must not only address these enormous ranges of scale, but also incorporate the exposure and effects of organisms ranging from microbes to humans. While the field of marine science does transcend the physical, chemical, geological and biological sciences, there are many other disciplines, including biomedical and socioeconomic, that are needed to fully assess the impacts of marine contaminants on environmental and human health. Moreover, contaminant problems in marine systems are only one dimension of the myriad of environmental challenges that must be addressed. These challenges will require researchers of different disciplines to come together and transcend institutional and disciplinary barriers to integrate their knowledge into a novel synthesis that will help to explain the dynamics of the complex global system.

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